Searching for a Low-Mass Higgs Boson with Light using Fermilab Collider Data

Abstract

High-energy photon data from the CDF experiment at Fermilab were studied to
search for the Higgs boson, a theoretical particle that has not been observed
experimentally. It is hypothesized that a Higgs boson that doesn't couple to fermions
(fermiophobic) could be created by proton-antiproton collisions at the Tevatron.
Computer programs (C++, LaTeX, and ROOT) were used to analyze detector data and
compare it with theoretical predictions and detector response simulations. Code was
developed to incorporate the latest Tevatron data and to calculate the efficiency
(including time dependence) of the analysis program and the detector in recognizing
radiation from Higgs decay. As a result of this work, a scaling factor relating detector
output to simulation has been developed which is applicable to high-energy electron or
photon events incorporating the most recent CDF data. In addition, a hypothetical Higgs
signal peak on top of background events has been generated. With these tools in place, a
lower limit on the mass of the fermiophobic Higgs boson was calculated. This limit is one
of the most stringent in the world derived from collider experiments of this type.

Introduction

As described by the Standard Model of particle physics, all matter in the universe
is composed of a small number of fundamental components. It divides these components
into three types; leptons, quarks, and bosons. However, very few of these particles are
found in matter found on earth or in our solar system, the rest having been discovered
through high-energy particle physics. These experimental discoveries confirm the
Standard Model's predictions, and have led to its widespread acceptance in particle
physics. Most recently, the discovery of the top quark in 1995 by Fermilab physicists
confirmed the existence of a sixth quark expected by the Standard Model [1] [2].
Although this model accurately describes many physics phenomena and several of its

predictions have been validated by experiment, there are other models or expanded version of the Standard Model that explain the universe differently. An important concern regarding the Standard Model is its explanation of particle masses; it postulates the existence of another boson, called the Higgs boson, whose eponymous field accounts for the mass differences of the fundamental particles [3]. This prediction, if confirmed, would give the Standard Model greater validity and also lend to its comprehensiveness. However, the prediction cannot at this time be disproved, as accelerator technology cannot reach the energies required to search the entire Higgs mass range [4]. With the importance of this prediction in mind, our Inquiry research was intended to answer (as best as possible) the question: Does a Higgs boson exist?

The existence of a Higgs boson is arguably the most significant unproven prediction of the Standard Model. As a result, it is being searched for in physics institutions across the world through various studies [5]. If it does in fact exist, the Higgs boson is expected to decay very quickly (on the order of far less than a nanosecond) into other less exotic particles. Therefore, the discovery of a Higgs boson (as with other high-mass exotic particles) will be facilitated by examining and searching for its decay modes. The particles to which the Higgs boson decays are also predicted by the Standard Model, but the investigation of these decay modes have proved fruitless at the current energies available [6]. By the equation $E = mc^2$, the energy required for the creation of a Higgs boson is proportional to the square of its mass; therefore, the mass range that we can search within is limited by the energy of the accelerator [7]. Extensions to the Standard Model's predictions also propose the existence of one or many Higgs bosons, but allow for different modes of decay. One extension of this model assumes a 'fermiophobic' Higgs, meaning that it cannot decay directly into fermions and must first decay into other bosons. Fermions are defined as particles with half-integer 'spin', which is a quality of subatomic particles, whereas bosons have integer spin [8]. As a result of these 'bosonic' tendencies, the Higgs boson in this model can be searched for by examining decay into photons, which are classified as bosons under the Standard Model and its extensions [9]. Although decay into photons is also expected to occur in the Standard Model Higgs, its

branching fraction (the probability that a certain type of decay will occur) is about two orders of magnitude smaller than that for the fermiophobic Higgs [10]. The branching fractions for the Higgs decay modes are shown in Figure 1. Our study involves the fermiophobic framework and deals with the analysis of photons in the search to prove the existence of the Higgs boson.

Finally, in high-energy physics, computer simulations such as Monte Carlo (MC) are often used to compare with data experiment. When calibrated correctly, these simulations allow physicists to see differences between what the Standard Model (or another model) predicts and what actually occurs in the collider. This feature is useful in our search for a fermiophobic Higgs boson because it helps us to determine when a fluctuation is statistically significant, among other things [11]. However, the calibration of the simulation is difficult because of small inaccuracies in the way the simulation predicts the response of the detector. Therefore, a calibration factor or scale factor is necessary in order for a direct comparison of Monte Carlo and data from the Tevatron to be made. In order to increase the accuracy of our search for the Higgs boson, we decided to find this scale factor as part of our study. The calculation of a scale factor requires the use of a well-documented decay mode, which allows us to be sure that the simulation and the data should agree. If they don't agree exactly, a series of calculations results in a scale factor that can be used in the search for the Higgs boson [12].

Materials and Methods

Accelerator and Detector Background

The analysis was made possible by Fermilab's particle accelerator, the Tevatron, and one of its two detectors, called the Collider Detector at Fermilab (CDF). The Tevatron gets its name from the energy scale that it operates at; particles can be accelerated until they have up to one tera-electron volt (TeV) of energy. Currently, this is the highest-energy accelerator in the world. The Tevatron is a circular accelerator almost four miles in circumference, and uses extremely powerful superconducting magnets in

combination with radio waves to accelerate and steer protons and antiprotons [7]. An aerial image of the Tevatron ring can be seen in Figure 2 with the proton injector ring in the foreground. These particles are focused into beams of more than 10^{14} particles each through precise placement and use of magnets, then the proton beam and the antiproton beam are made to pass through each other, meeting once every 396 nanoseconds. Once the process of proton-antiproton collision has begun, the detector allows physicists to pick only the collisions they want out of the millions per second that occur [13].

The CDF detector weighs 100 tons and records various attributes of the particles created by proton-antiproton collision. The detector can be seen in Figure 3. Millions of such collisions occur each second, but only a few are worth examining. Most collisions involve contact between the 'point particles' that make up protons and antiprotons, but only a few situations result in collisions that are energetic enough to create the exotic particles that physicists are interested in studying. A group of computers is able to distinguish the valuable events almost instantaneously by checking whether an event passes or fails certain requirements. These requirements are collectively known as a trigger, and thus the process of recording only the potentially interesting collisions is called triggering. The data from each of the collision events passing the trigger is then recorded, and can be used for studies like this one that investigate rare particles [13].

The detector is composed of several layers, each detecting separate properties of the particles that pass through them. The first is the Silicon Vertex Tracker, which is very sensitive and can record the track of charged particles to within ten microns. Its name comes from the ability to reconstruct the vertex that a particle originated from, helping researchers to determine whether a particle resulted from the initial collision of protons and antiprotons or if it was a product of later decay. The next layer, the Central Tracker, measures the momentum of charged particles by their bending in a magnetic field. The following two layers are the Electromagnetic Calorimeter and the Hadronic Calorimeter, respectively, and can measure the energy of most particles created by the collision. Electromagnetic particles like photons and electrons deposit the majority of their energy in the Electromagnetic Calorimeter, measured by a scintillator material that gives off light proportional to the energy of the particles. A similar process occurs in the Hadronic

Calorimeter, except that it measures other particles called hadrons, which were not examined in this study. The last two layers are an iron absorber to stop most particles that didn't lose all of their energy in the calorimeters, and a muon detector to record any that penetrated the absorber (most of these particles are muons). Electrons, which are used in the first part of the study, are tracked mainly by the Silicon Vertex Tracker, the Central Tracker, and the Electromagnetic Calorimeter. However, photons, which do not carry a charge, only interact significantly with the Electromagnetic Calorimeter and are central to the second part of the study. Finally, the detector at CDF is divided into two parts: a central region, which can track particles the most accurately, and two plug regions (seen head-on in Figure 3) which have less accuracy [13]. As misidentification can occur more easily in the plug detector as a result of this difference, our study excluded events in which two particles appeared in the plug region. Finally, differences between the central detector and those in the plug detector must be accounted for in this study and other physics research.

Analysis

The bulk of the work done for this Inquiry project applied to one of two objectives; calculation of the Monte Carlo scaling factor, and calculation of a lower limit on the fermiophobic Higgs boson mass. The scale factor study involved determining the detector's (or the simulation's) efficiency, or its chance to identify certain particles. For this study, the Z boson was chosen because its mass is well known and its decay yields what is called a 'pure sample' of electrons (two per boson), comparable to the fermiophobic Higgs decay into two photons. This similarity is useful because electrons and photons leave similar data in the detector, and so they can be identified using similar criteria. The mass of the Z boson is known to be 91.19 giga-electron volts (GeV), so a histogram showing the combined mass of electron pairs should have a peak at around 91.19 GeV as shown in Figure 4. The scale factor study analyzed all events with electron pair candidates that had been recorded by the detector. Each electron pair was examined to determine its combined mass and other variables such as momentum and detector

positioning to make sure that it was an electron. If an electron passed these requirements (also known as tight cuts) it was identified as a real electron [14]

The efficiency of the detector at identifying electrons was defined as the number of electrons passing all of the tight cuts divided by the number passing loose cuts (those that qualify it as a possible electron event). The Z boson was chosen for this study because of the fact that two electrons are created for each Z boson, and so if one is identified as a true electron, the other should be too. However, a bias is created if two electrons are measured in the central detector, because the 'better' electron candidate is chosen to be the tight leg, while the other is analyzed to determine the efficiency. This results in a lower probability of the second electron passing tight cuts, because it is automatically selected as the worse of the two. The efficiency equation for central electrons (E_c) was modified to account for this bias. The resulting equations for efficiency are shown below [12]:

$E_p = N_{TT} / N_{TL}$ Used for plug efficiencies

$E_c = (N_{Ti} + N_{TT}) / (N_{TL} + 2N_{TT})$ Used for central efficiencies

In these equations, E represents the efficiency, N_{TT} the number of events passing tight cuts, N_{TL} the number of events passing loose cuts, and N_{Ti} the number passing cuts up to and including the ith cut [12]. In total, the scale factor study checked all electron pairs to determine whether they passed the tight electron cuts, the number passing cuts was then used to calculate the efficiency of the detector in identification using the above equations. This program was run on electron data from the Tevatron, which is grouped into thirteen periods. In addition, it was run on a sample of electron pairs resulting from Z boson decay simulated by MC. The result of this analysis was a series of calculated efficiencies for each period of the Tevatron data and efficiencies for the pure electron sample. After these efficiencies had been calculated, scale factors were calculated and then studied as a function of run period (see Figure 5).

Once the scale factor study had been completed and the value of the average scale factor had been calculated, the search for the fermiophobic Higgs boson was able to

continue. The Higgs study first identified pairs of photons resulting from the Higgs boson
decay. Photon pairs were analyzed to check that they passed an array of photon cuts
(similar to electron cuts except for the requirement of a track) to confirm them as
photons, and then efficiencies were calculated as in the scale factor study.

For the Higgs search, these cuts serve to remove background events, even those in which
a pair of real photons was detected; they eliminate as many events as possible that don't
have the signature of a Higgs boson decaying into two photons. The histograms showing
all photons passing the tight cuts were examined for signs of significant excess over a
smooth background curve (see Figure 6), which could indicate a new particle at that mass
point. In this study, the analysis of Monte Carlo simulated data (after application of the
scale factor) yielded the efficiency of the detector for identifying the Higgs. This
efficiency, which was calculated at various mass points, was significant because it is part
of an equation used to calculate the number of Higgs events that should occur. The
equation is shown below:

$$N = L\sigma E B_r$$

In the equation, N is the number of Higgs events that should be accepted into the
analysis, L is the integrated luminosity, σ is proportional to the probability of a Higgs
being created, E is the efficiency, and B_r is the branching fraction. The integrated
luminosity is proportional to the amount of data used and could be easily calculated,
while σ and B_r are predicted by theory, then tested by experiment. Finally, the efficiency
was calculated according to the method detailed above. If an excess of events over the
Standard Model's background prediction was observed, the magnitude of this excess
would be taken as N, allowing $\sigma \times B_r$ to be extracted using the above equation. However,
no excess was observed, so a statistical (95% confidence) limit was placed on N by
comparing the observed data with a simulated Higgs peak. Figure 7 shows the size of the
peak that we would be sensitive to on top of a background curve; any peak with N greater
than that in the chart would be evidence for the Higgs boson. This amounts to an upper
limit on N. Using this limit, an upper limit on $\sigma \times B_r$ was calculated with the above
equation. Furthermore, σ for the Higgs boson is predicted by the Standard Model, so a

limit on the single variable B_r could be calculated if this σ was assumed to be correct. Finally, because the calculation of this limit depends on efficiency –which fluctuates as the mass of the photon pair changes – the branching fraction limit had to be calculated more than once. These branching fractions were plotted against the mass of the photon pair, and then compared with the branching fractions predicted by the fermiophobic Higgs model. The intersection of our limit with the prediction was taken as the limit on the Higgs mass, shown in Figure 8. For any masses above this limit, the prediction for the branching fraction is below the calculated lower limit, and therefore N for that mass would be too low to be statistically significant.

Results

In order to search for the decay of the Higgs boson to two photons, the scale factors between data and simulations were calculated to be 97.2% for central-central events, and 94.3% for central-plug events. The scale factors [14] are shown in Figure 5. These results were then used to continue the Higgs search. Although this study did not result in the discovery of a Higgs boson decaying to two photons as described in the fermiophobic model, it did result in the calculation of a lower limit of 102.5 GeV on the mass of the Higgs boson predicted by this model. In comparison to previous CDF research, our study improved the Higgs limit and the line of the cross section limit, shown in Figure 8. This is the strongest limit yet achieved by a hadron collider.

Discussion

The calculation of scale factors of 97.2% (central-central) and 94.3% (central-plug) between Monte Carlo simulation and actual detector response accounts for the inaccuracies of the simulation and reconciles its predictions to data from the detector. This scale factor can be used for other studies involving high-energy electromagnetic radiation. In addition, the graph showing the scale factor for each period does not reveal a significant time-dependence; therefore, it can also be applied to research involving new data. This eliminates the necessity to continue calculating scale factors as data is added.

In addition, we were able to place a lower limit of 102.5 GeV on the mass of the fermiophobic Higgs. If the Higgs boson had existed below this mass, we would have seen statistically significant evidence of it, as demonstrated in Figure 7. This limit improves the accuracy of the previously calculated limit, 99 GeV. It is also the highest (second-highest) limit for the fermiophobic Higgs from any hadron collider in the world. The only higher limit, 109.7 GeV, has been calculated by LEP in Switzerland using electron-positron collisions. A higher energy study would increase the mass range we are sensitive to and therefore could improve the limit; the only other way to improve this limit is by increasing the total luminosity, which is proportional to the amount of data available. It is hoped that methods made here will be valuable to future studies of the fermiophobic Higgs, especially those that can achieve higher energies. Other decay types for the fermiophobic Higgs could also be tested in order to place a limit on the mass and check the results of this study. Notably, our limit of 102.5 GeV nears the mass range where the fermiophobic Higgs decays into photons very infrequently, preferring the H » WW channel. Therefore, to set a more stringent limit it might be valuable to examine this decay mode.

The Higgs boson is one of the most important unverified predictions made by the standard physics model, and is being searched for across the world. This helps all of these researchers by reducing the mass range and decay modes that they have to search within. Effectively, it helps to narrow down at what mass and in which theoretical model the Higgs will fit into. These results compared favorably to previous studies of the fermiophobic Higgs by Craig Group and Callie DeMay [15] and the D0 Collaboration [16]. Our limit did not reach the limit of 109.7 GeV set by LEP at CERN [17], but it improves upon previous results from hadronic colliders.

This Inquiry project incorporated more data into the search for the fermiophobic Higgs and increased accuracy through the calculation of a scale factor. Regardless of these differences, the limit on the Higgs mass was not expected to change significantly, in keeping with our result of 102.5 GeV. However, the study was important in that it

furthered the search for the Higgs boson and incorporated all of the applicable CDF data to date.

Conclusion

After a year of work, we feel that our research has effectively ruled out the possibility of a fermiophobic Higgs boson existing with a mass of less than 102.5 GeV. This result is the culmination of several other analyses that had to be completed before we could calculate the limit. For example, our calculation of two scale factors for high-energy photons is significant in that they can be re-used by other photon research at CDF, saving others time. Most importantly, however, this limit on the Higgs mass is the best ever achieved at a hadronic collider and paves the way for an even higher limit once more data and/or higher energies become available.

Inquiry Process

The vast differences between an Inquiry project and a standard science class (even at IMSA), allow for another style of education and progress. For me, the idea that I was actually participating in 'new science,' doing something that had the potential to yield a discovery or that could be instrumental in someone else's discovery changed the way that I approached the work. My goal wasn't a grade; rather, it was to accomplish the work that I was expected to do and get an idea of what working in particle physics would be like. I felt more fulfilled because this experience was more like a job instead of a class, with concrete and significant results. However, the experience was difficult in that I had to direct my own learning – as my advisor had other work to do – and I had to be sure to concentrate myself and maintain self-discipline in order to achieve my goals. There was rarely anyone telling me what to do in any specific capacity, or how to accomplish my tasks. As I quickly learned, CDF is a place where actual science is done everyday and physics discoveries are made: in contrast, when in the classroom, we talk about things that people have known for decades or centuries, and any experiments we do have been done thousands of times before. At CDF, everyone is working on adding something new

to the research that has already been completed. These differences gave me a radically different impression of science than I had before my SIR project. Of course, there were many problems with this approach to learning, among them the difficulty of applying a deadline to such research, changing direction in order to calculate our scale factor, and self-teaching of programming and physics theory. That isn't to say that my advisor didn't help me with the programming or the theory aspect of our work; however, there was plenty of room for me to teach myself and be independent. For example, when I began the project I thought that we would be analyzing photons to search for the Higgs boson for the entire year, which at the time wasn't very exciting because I didn't know how to do anything useful. Soon, we realized that we could do a scale factor study in order to increase the accuracy of the Higgs research. This intermediate study allowed me to learn much more quickly because it was simpler, and also gave me a chance to write several thousand lines of programming code and observe a formal physics presentation. Thus, although my greater degree of independence was sometimes a challenge, through effort and dedication I was able to convert it into a more rewarding learning experience than I normally find in class.

Acknowledgements

I thank Dr. Craig Group, Dr. Ray Culbertson, and Dr. Mike Lindgren for taking so much of their time this year to teach me about particle physics and develop my skills. It took a long time before I was ready to make a real contribution to the work, but I did my best to repay their investment in me. At times they may have been discouraged by my lack of experience and knowledge, but their perseverance facilitated our collective discovery of this limit. In addition, I thank the SIR program and its coordinators, without whom I could never have enjoyed this opportunity. Finally, I would like to thank my mother for helping me to participate in this Inquiry, by driving me to Fermilab so that I could keep up with other obligations.

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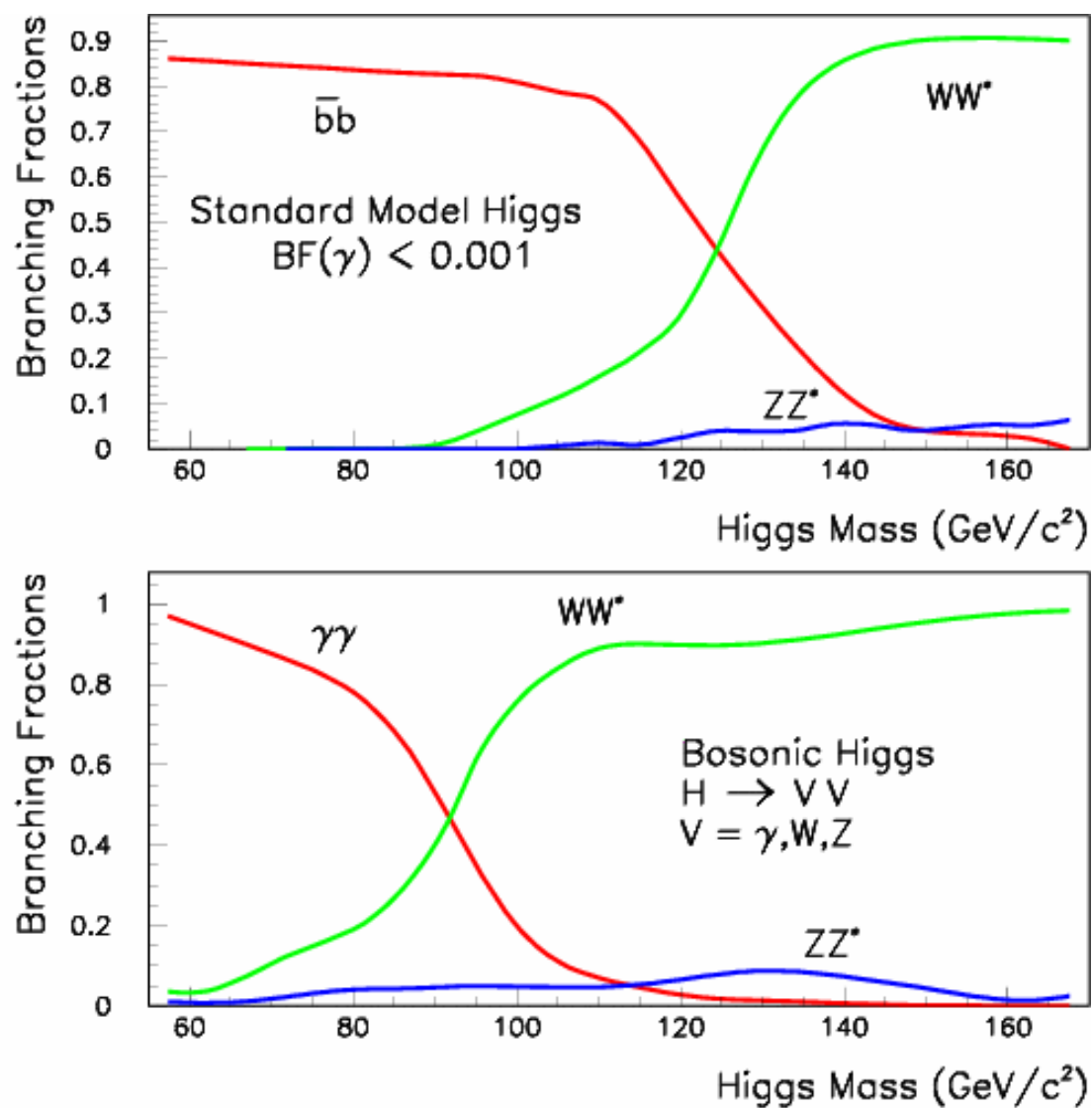[18]   CDF. (2005). "CDF Pictures." Fermi National Accelerator Laboratory. Batavia, IL. [Online]. Available: http://www-cdf.fnal.gov/events/CDFPictures.html

Figure 1: Branching fractions for Higgs decay in the Standard Model and Fermiophobic extension.

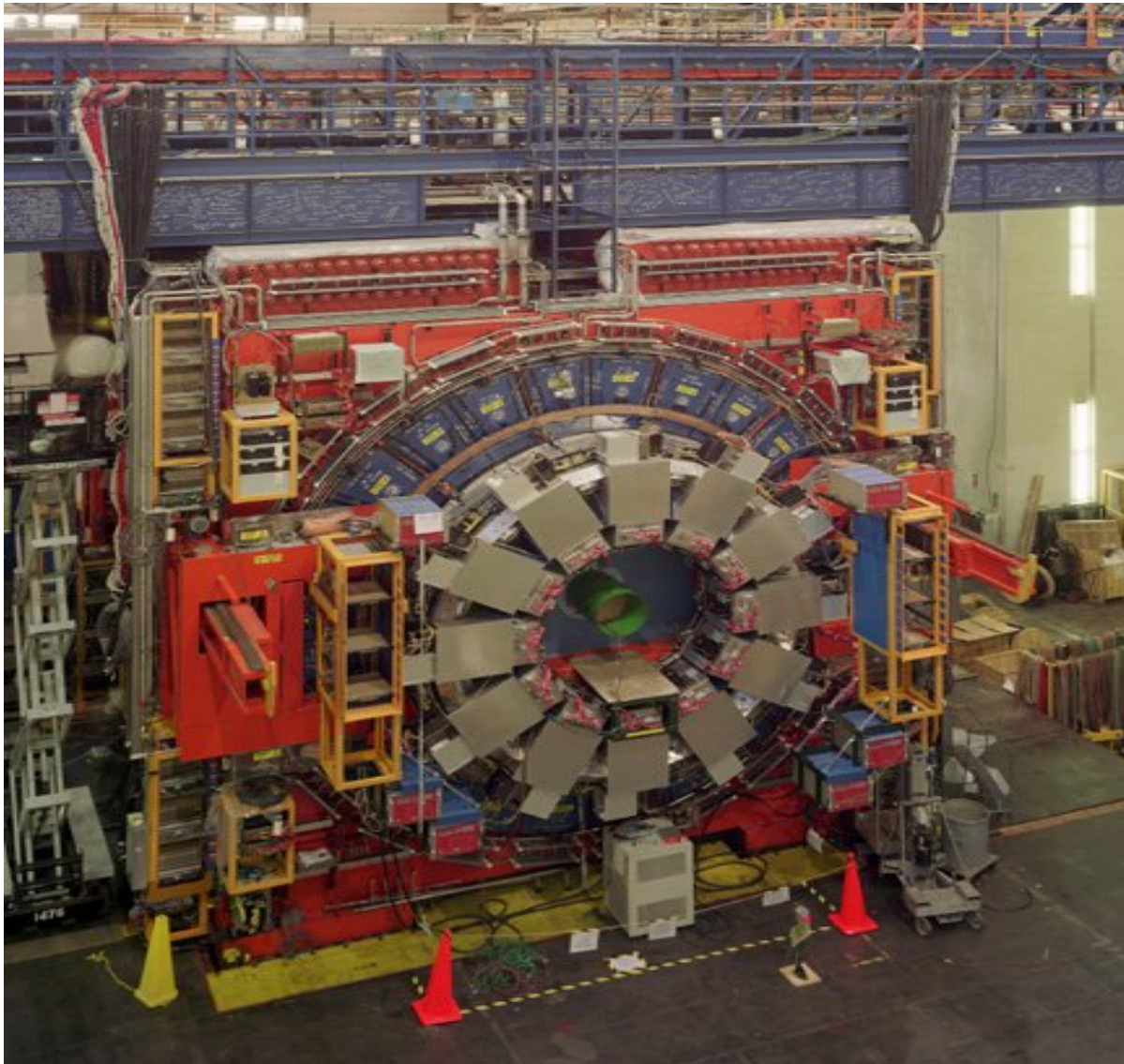**Figure 2: Aerial view of Fermilab's Tevatron Accelerator ring, with the Main Injector visible in the foreground [18].**

Figure 3: View of the 100-ton CDF detector during installation, showing the plug region [18].
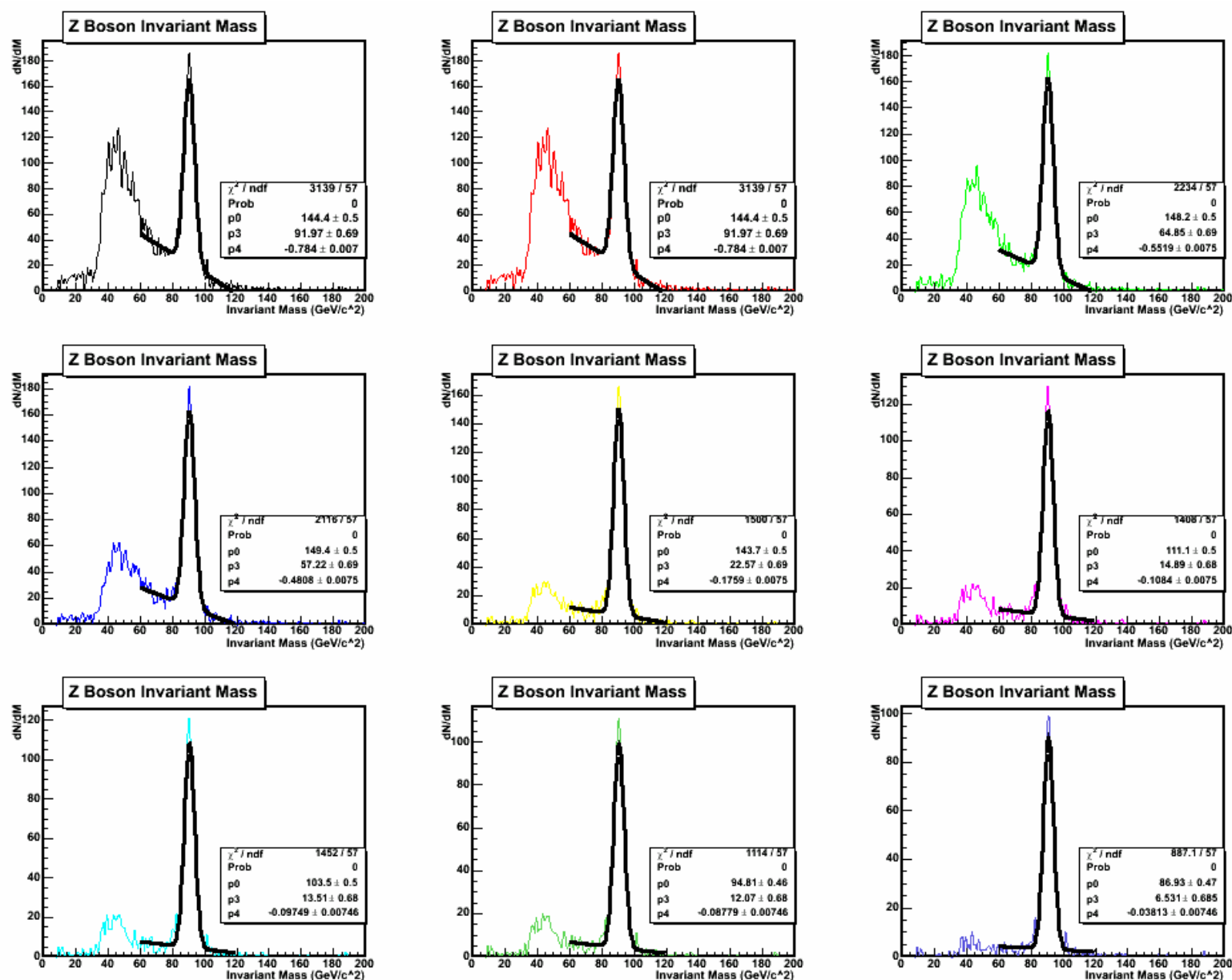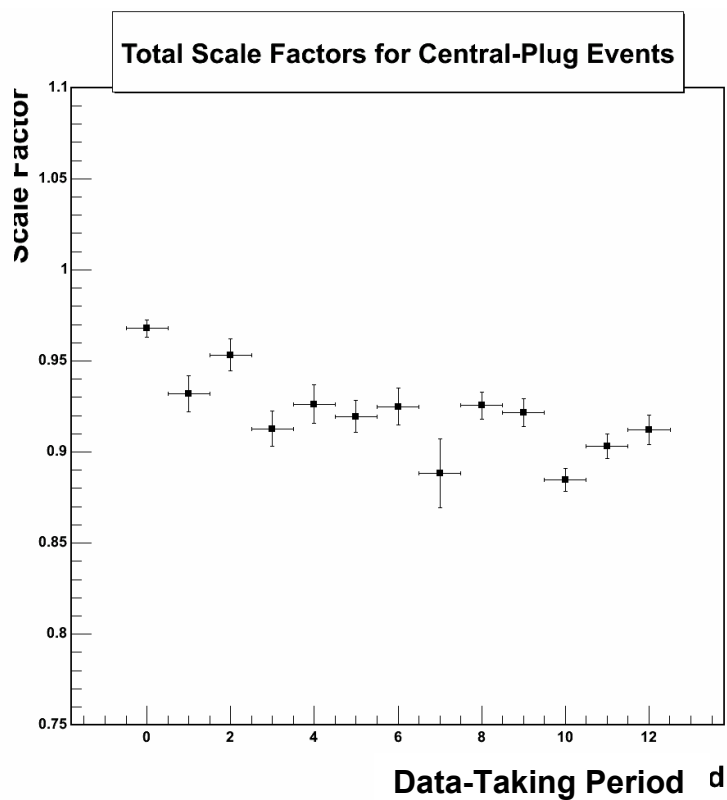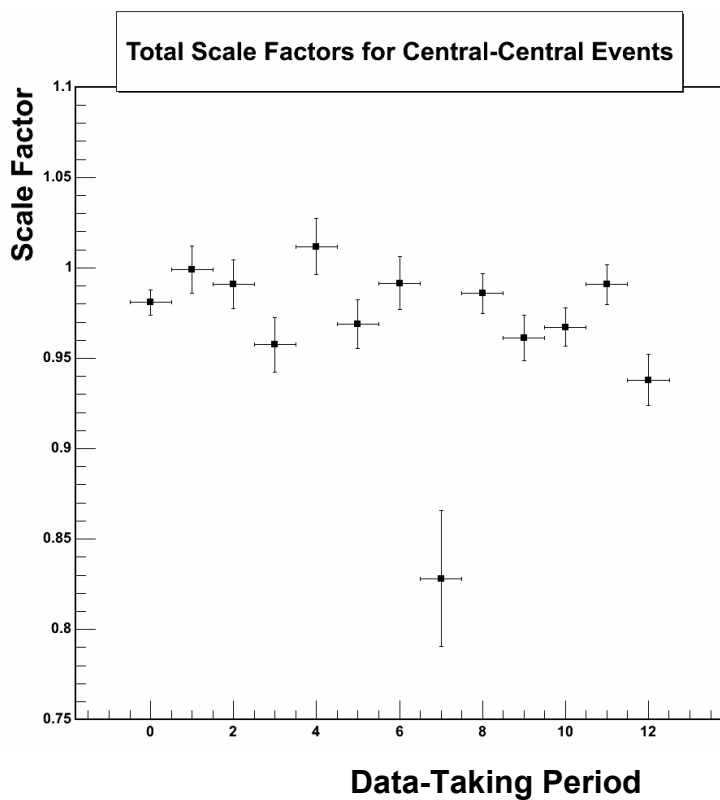
Figure 4: Z Boson signal peak showing the removal of background from each cut and the fit used in calculations.

Total Scale Factors for Central-Central Events

Total Scale Factors for Central-Plug Events

Figure 5: Graph of scale factor vs. period number with error bars for central-plug events. As seen in the graph, no significant run dependence was found.
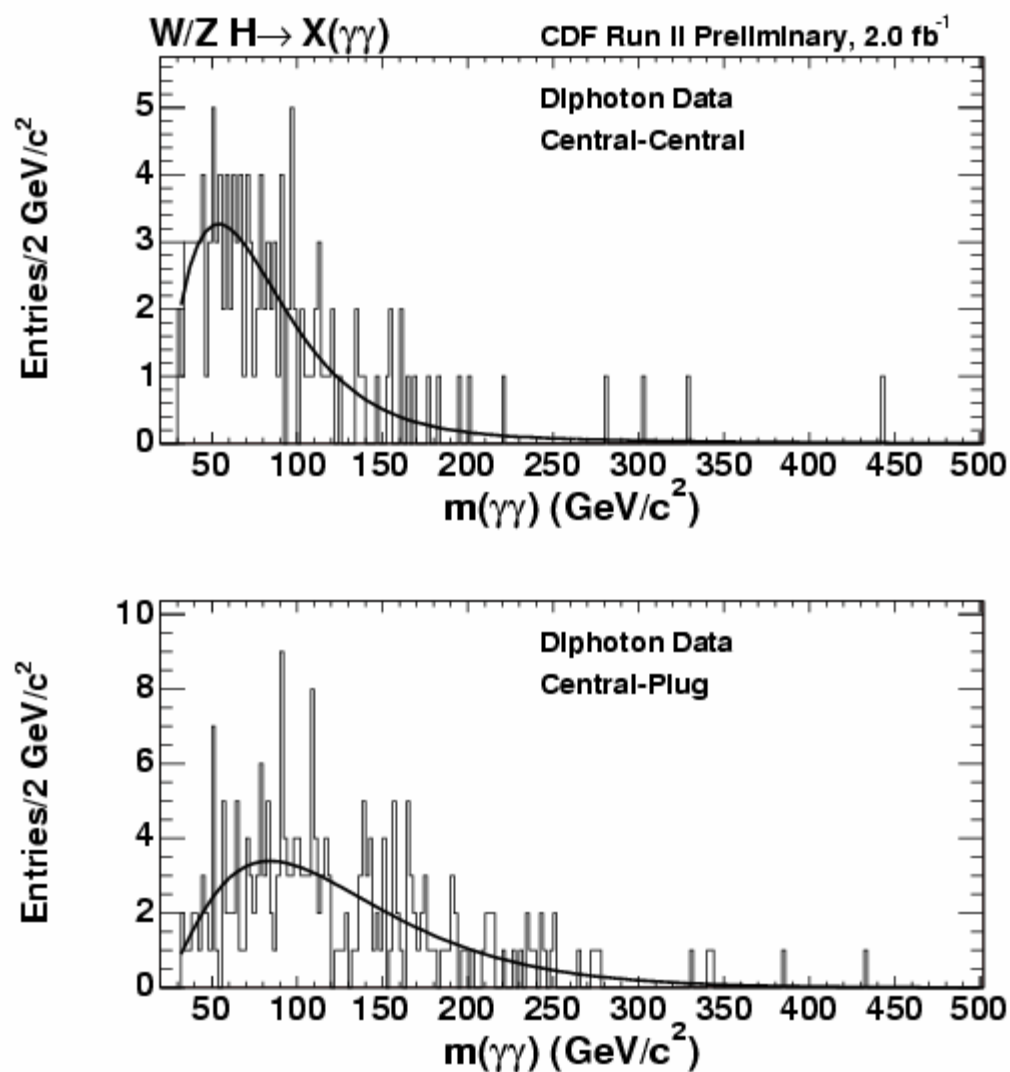
Figure 6: Histograms showing the number of events passing tight photon cuts for masses up to 500 GeV, with fits.
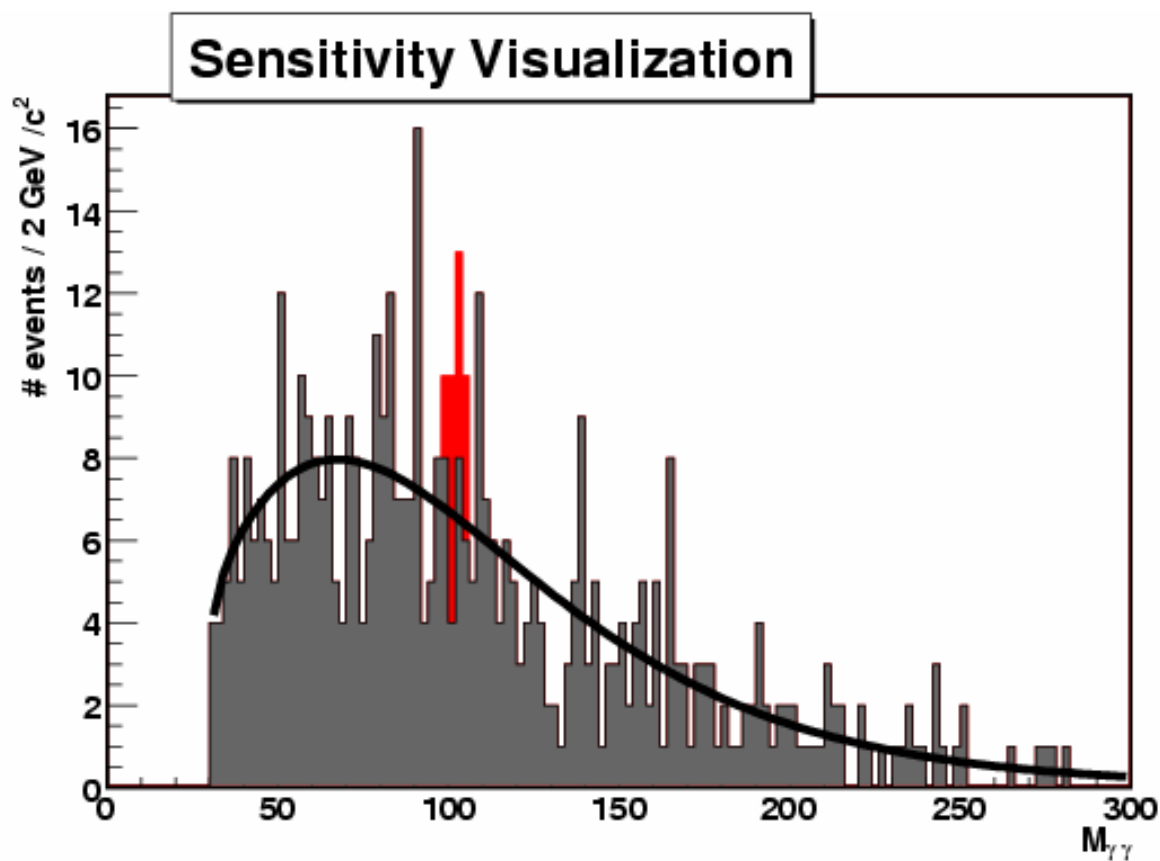
Figure 8: Plots showing the benchmark predicti

Figure 7: Histogram showing the background events from the Higgs study in grey and a peak with N = the upper limit on N in red to illustrate the study's sensitivity.
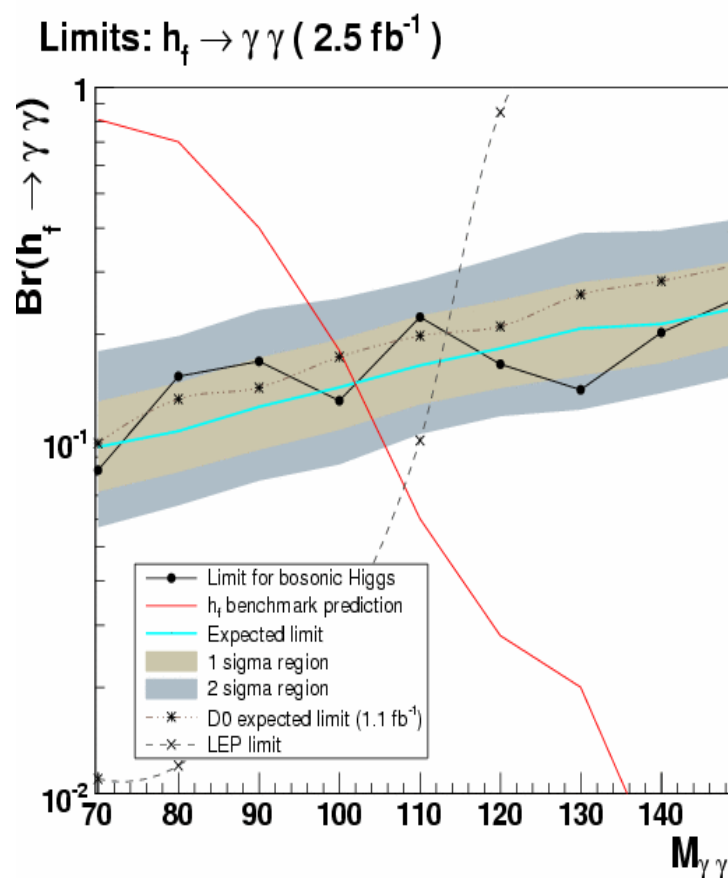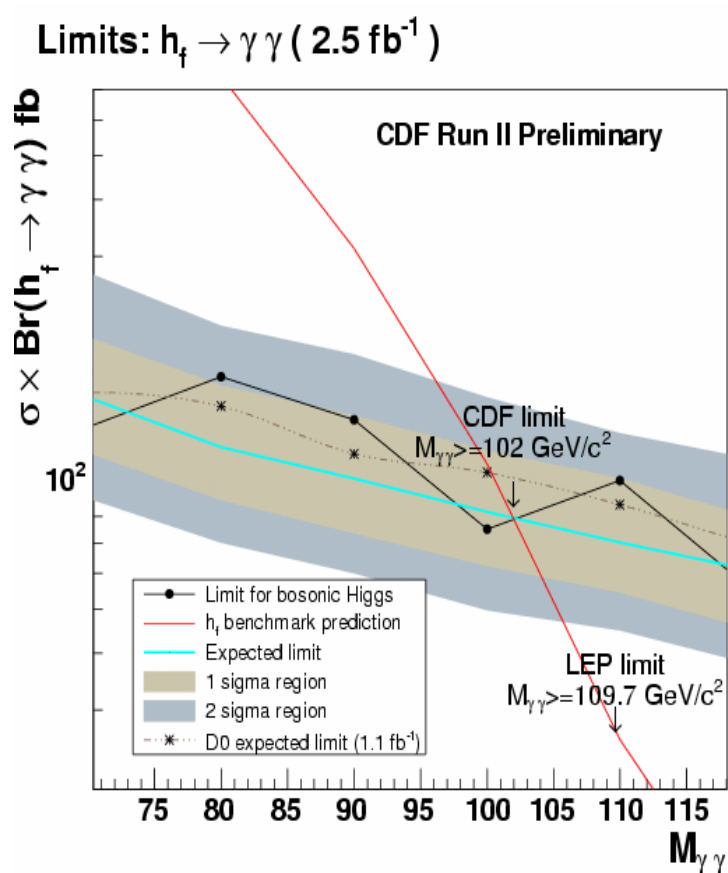
Figure 8: Limit plots showing the intersection of the fermiophobic model's predictions for Br x σ (right side) or simply Br (left side) with the limits calculated by the Higgs analysis. The left plot includes the current highest limit from LEP.